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STUDY OF STRESSES AND VIBRATIONS OF A VIRTUAL ELBOW ORTHOSIS MODEL BASED ON FINITE ELEMENT ANALYSIS

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Abstract: *The principal objectives of this research endeavor are to mitigate the symptoms associated with osteoarthritis, including joint discomfort and restricted mobility, thereby enhancing patients' overall quality of life. In addressing this research topic, a three-dimensional virtual modeling approach was employed to generate a representation of a market existent physical orthosis, which is frequently used in clinical rehabilitation of the elbow joint. Finite element analysis (FEA) was performed to ascertain the elastic behavior of an elbow orthosis model and its effect on the hand-arm system during demanding instances of customer usage using the Ansys software. A data acquisition platform (Biometrics Ltd.) was utilized to meticulously document elbow flexion-extension and pronation-supination prior to and following a rehabilitation program implemented for a patient affected with osteoarthritis disease.*

Key words: *Elbow orthosis, rehabilitation, vibration, stress, electrogoniometers, elbow osteoarthritis, FEA*

1. INTRODUCTION

The elbow is classified as a synovial joint, which is characterized by its exceptional range of motion (ROM). The elbow joint is indispensable to a wide range of activities, including flexion-extension, pronation-supination. The anatomical composition of the joints consists of a cavity in one bone, lined with the synovial membrane of the other bone. The extremities of the bones that constitute a synovial joint are enveloped by slippery hyaline cartilage. The synovial membrane, an aqueous sac that lubricates and protects the joint, is present in the interstices between the bones. The provision of this additional protective layer serves to reduce surface friction during movement, thereby facilitating a greater degree of joint efficiency and ROM. The elbow joint is composed of several key components, as illustrated in Fig. 1. Osteoarthritis is a condition that arises from the gradual degeneration of the cartilage in a joint due to prolonged exposure to friction and mechanical stress [1]. This pattern is characterized by patients' frequent reports of pain at the end of the ROM for both flexion-extension or forearm rotation. It has been determined by researchers that a considerable number of challenges have been identified in the process of measuring and subsequently understanding hand-arm vibrations. This is especially relevant when such vibrations are associated with the use of an orthosis system, the purpose of which is to increase both mechanical stiffness and stability. As demonstrated in study [2], this complexity poses a substantial obstacle in measurement efforts. A series of standards has been developed in order to facilitate the consistent analysis and interpretation of hand-arm vibrations. A subset of these standards addresses all categories of hand-transmitted vibrations, including DIN EN ISO 5349-1:2001 [3] and DIN EN ISO 5349-2:2001 [4].

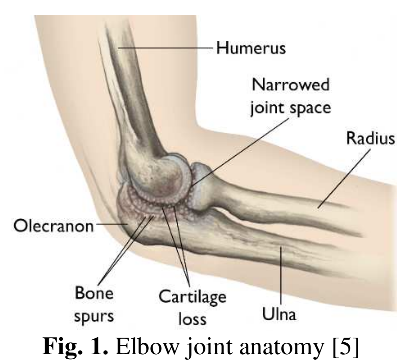

Fig. 1. Elbow joint anatomy [5]

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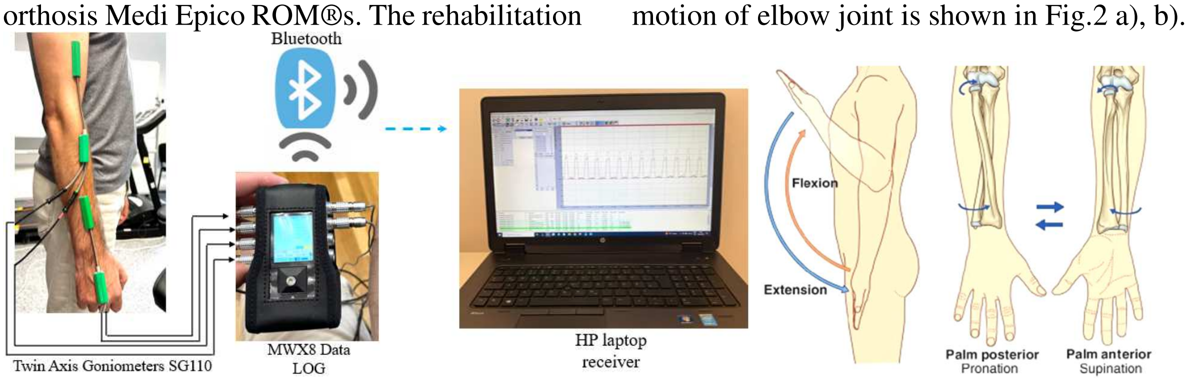
2. EXPERIMENTAL PROTOCOL

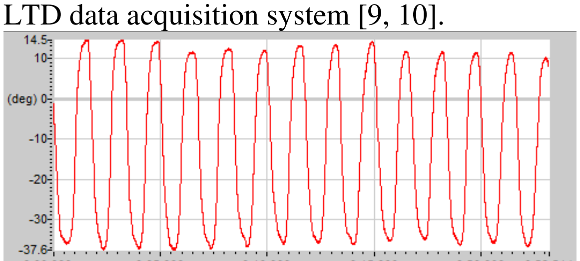
The experimental tests, consisting of flexion/extension and pronation/supination movements of the elbow joint, are performed by a patient suffering from elbow osteoarthritis, seven times, 15 consecutive cycles each, both before and after two months of performing the movement rehabilitation program with the orthosis Medi Epico ROM®s. The rehabilitation program was designed to improve elbow range of motion (ROM). The equipment used for biomechanical data acquisition is Biometrics system, which is based on wearable sensors like electrogoniometers and torsiometers, often used in biomechanical and clinical research [6-8]. The patient gave written consent to participate in the experimental study. The schema block of acquisition process and functional range of motion of elbow joint is shown in Fig.2 a), b).



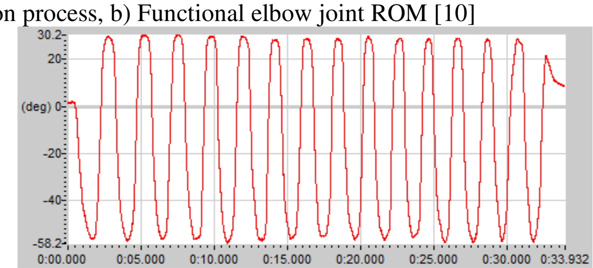
a) b)

Fig. 2. a) The block schema of the data acquisition process, b) Functional elbow joint ROM [10]

The biomechanical data is transmitted in real time from the wearable sensors to the wearable device Data LOG and then, via Bluetooth, to the computer. The diagrams of consecutive movements cycles are plotted in real time on the computer's screen. The experimental tests were approved by the Ethics Committee of the University of Craiova. The experimental result shown in Fig. 3 indicated a positive outcome, as evidenced by an enhancement in ROM. For flexion/extension, the amplitude increased from an average value of 90° to an average value of 124° after rehabilitation. Similarly, for pronation /supination, the angular variation increased from a range of 12° to an average value of 29° after rehabilitation. The equipment used for data acquisition was the MWX8 Data LOG device (129 grams) which works within the Biometrics LTD data acquisition system [9, 10].



(a)



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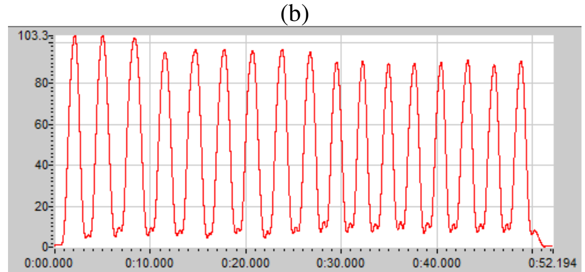

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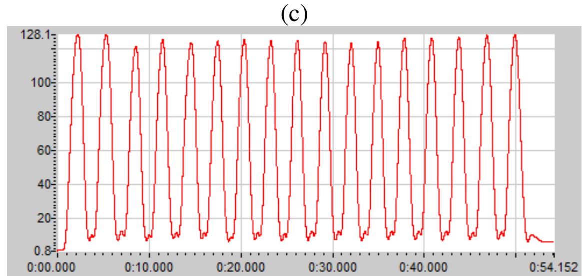


(d)

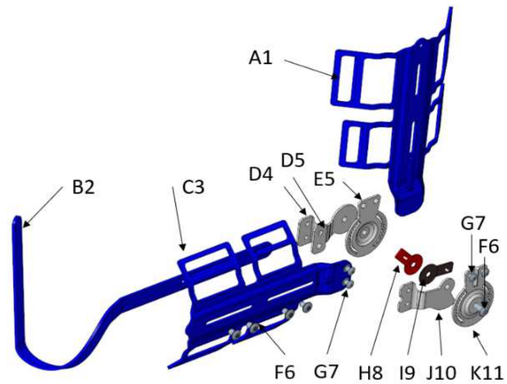
Fig. 3. Pronation/supination angular variation [deg] a) before rehabilitation, b) after rehabilitation; **Elbow flex-ext.**[deg]: c) before rehabilitation, d) after rehabilitation.

3. VIRTUAL 3D ORTHOSIS MODEL

In this study, the virtual 3D model of a widely recognized elbow orthosis, frequently employed in clinical elbow joint rehabilitation protocols, is meticulously elaborated and analyzed with a focus on its design intent. The extended hand support of the Medi Epico ROM® splint, with its soft material, ensures better comfort. The orthosis is characterized by its ability to enable personal flexion and extension movements in 10° increments. This adjustment allows for a range of motion extending from 0° to 90° in the extension direction and from 0° to 120° in the flexion direction. The orthosis offers a stable and reliable fit, providing consistent support throughout the day. It is designed to facilitate physiotherapy and mobilization exercises, ensuring that the wearer experiences minimal discomfort or restrictions during these activities [11]. The Medi Epico ROM®s (Fig.4 and 5 – explode view and components exemplifications) is an elbow orthosis for mobilization or immobilization of the proximal radioulnar joint. The soft fabric hand rest ensures great wearing comfort. The non-slip coating on the forearm can be reduced to suit the user's individual fit. This ensures effective support daily and during physiotherapy and mobilization exercises [12].

Fig. 4. Medi Epico ROM®s orthosis

The virtual model of the orthotic device was initiated with a series of sketches for each component, following the measurement process. These sketches were then transformed into solid models through a process of modeling and reconstruction. Concurrently, a range of analytical procedures was employed, leading to the generation of results that could be corroborated by existent literature in the field.



A1 - Upper arm support, B2 – Extended forearm support, C3 – Forearm support, D4 – Forearm frame 1, D5 – Spacer, E5 – Arm hinge for adjusting the locking angle, F6 – Bolt joint, G7 – Rivet joint, H8 – Adjusting key (extension), J9 – Adjusting key (flexion), J10 – Forearm frame 2, K11 – Forearm hinge for adjusting the angle.

Fig. 5. Medi Epico ROM®s – explode view.

The construction of the three-dimensional model of the orthotic devices was facilitated by the Creo Parametric application. The dimensional characteristics and structural interrelationships of the model were derived from the physical orthotic device. The resulting model maintained a one-to-one ratio with the original device, thus ensuring precise correspondence between the two. The process of creating three-dimensional representations of orthoses entailed the utilization of various extrusion features in the context of three-dimensional modeling. This approach facilitated the conversion of two-dimensional sketches into three-dimensional extruded solid protrusions, with the thickness of each component assigned accordingly. The model was imported into the Ansys Space Claim preprocessor of Ansys Mechanical software and underwent a series of editing techniques and geometry verification. This procedure was implemented to remediate specific geometric discrepancies that might have emerged during the import process [13].

4. MATERIAL PROPERTIES

A review of the literature reveals that orthosis material should ideally possess three characteristics: reduce weight, reliability, and endurance [14,15]. Table 1 presents the material attributes utilized for the orthosis parts, including Density (ρ), Young modulus (E), Poisson ratio (μ), yield strength (**σy**) and Ultimate Tensile Strength (UTS).

Table 1.
Orthosis material characteristics [6, 7]

Part name	Material	ρ [Kg/m3]	E (GPA)	UTS [MPa]	[μ]	**σy** [MPa]
A1	Aluminum	2770	71	260	0.33	180
B2	Steel	7850	207	360	0.3	225
C3	Aluminum	2770	71	260	0.33	180
D4/J10	Steel	7850	207	360	0.3	225
E5	Steel	7850	207	360	0.3	225
K11	Steel	7850	207	360	0.3	225

Given the established parameters, the selection of aluminum alloy for the arm and forearm support is justified. Additionally, it exhibits comparable hardness and other characteristics, making it a viable option for the desired application. The utilization of standard steel in the fabrication of forearm hinges is predicated on the premise that it will offer adequate support. However, it is acknowledged that stainless steel possesses the potential to provide higher strength and offer superior fixation capabilities, particularly in scenarios where precise adjustment of the arm's position is paramount. Consequently, the utilization of stainless steel is recommended for applications in specialized environments where performance and durability are of the utmost importance [16-17].

5. FINITE ELEMENT ANALYSIS

FEA method is a valuable tool for analyzing the behavior of the human musculoskeletal system and, respectively, of structures used in their clinical studies. Many studies in literature have analyzed the behavior of human joints, as well as the orthotic or robotic systems used for their rehabilitation [18-23]. The development of realistic computational models can provide important information for biomedical research, for optimizing useful structures for the rehabilitation of human joint movements. In order to ascertain the structural integrity of the orthosis design, a series of computer-based simulations were conducted. These simulations incorporated static and dynamic loading conditions, thereby encompassing a comprehensive evaluation of the orthosis's capacity to withstand stress. Given the complex nonlinear characteristics exhibited by soft tissues and strips, their inclusion in the finite element process was not feasible. The numerical simulations were carried out using an HP Z840 high-end workstation. This computer is equipped with a high-performance Intel® Xeon® E processor and 250 GB of memory.

a. Boundary Conditions - The forearm support of the orthosis is fixed to restrict motion in all directions. The imposed load is applied at a central location on the support arm component, which is considered the central mass point of the orthosis and shoulder arm, detailed in Fig. 6. In this investigation, we focused on the primary contact algorithm between orthosis central mechanism components. This investigation incorporated frictional contact with a friction coefficient of 0.14 and an augmented Lagrange formulation. This formulation was used for the purpose of controlling penetration tolerances and producing qualitative results. It is important to note that all other contacts between components were bonded together.

b. Mesh Configuration - The mesh discretization consists of solid hexagonal elements of type 186. (Fig. 7. b). A preliminary stress analysis was conducted, in which critical regions were identified and examined. A sensitive study was also conducted, and the element size was recalibrated. The maximum element size was set to 0.5 mm for the observed regions. For adjacent areas, a maximum element size of up to 1 mm was implemented. The total number of nodes and elements for the analysis network can be viewed in Table 2, which provides a comprehensive overview of the orthosis mesh discretization metrics.

Table 2.
Mesh metrics (critical components).

Part name	Nodes	Elements
A1	656983	432554
B2	218925	139127
C3	572320	372731
D4	225750	149073
E5	297476	195226

J10	215483	141976

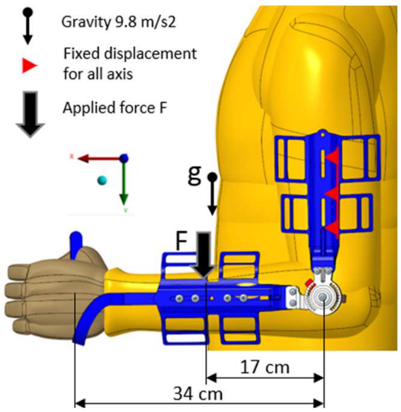


Fig. 6. Boundary conditions.

The mesh quality is shown in Fig.7 a). The final mesh consisted of 2.749.816 nodes and 1.781.875 elements.

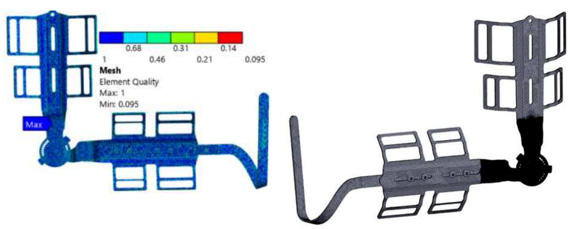


Fig. 7. a) Element quality, b) Mesh decomposition.

Static analysis - The objective of this calculation was to assess the stresses induced in the orthosis assembly due to rigorous customer-demanding usage. To this end, a virtual 3D geometric model for the orthotic device was created and used with the recent highlighted analysis settings and boundary conditions. The simulations were conducted for the purposes of assessing the stress state of the orthosis under flexion and extension static conditions, evaluating the response of the structure to dynamic loading, extracting eigenmodes frequencies. Static loading is defined by four load cases, with the initial load case starting at 10 (N), followed by subsequent load cases of 15 (N), 25 (N), to a maximum load of 35 (N).

Modal analysis is a method of analyzing vibrations that offers distinct advantages. It enables designers to avoid resonant vibrations, to compare different configurations, or to operate a structure within a certain frequency bandwidth. The configuration of the boundary variables was undertaken in accordance with the parameters of the research study [24-25].

6. ANALYSIS RESULTS

As illustrated in Fig. 8, 9, 10, the von Mises stress maps and total deformation plot Fig.11, are presented during the maximal selected test loading conditions of 35 N, while in Table 3, the outcomes for each of the four load parameters under examination are summarized.

The natural frequencies of the system under investigation were obtained through the utilization of ANSYS 2024R2 software tool. The mode shape results are presented in Fig. 12, respectively 13 and in Table 4.

Table 3.

Stress summary (Equivalent von Mises – [MPa]).

Force X	A1	B2	C3	D4	E5	J10
10 N	23	4	12	48	80	33
15 N	31	5	17	66	112	46
25 N	48	9	26	102	178	73
35 N	65	12	35	138	242	99
Stress criteria	180	225	180	225	225	225

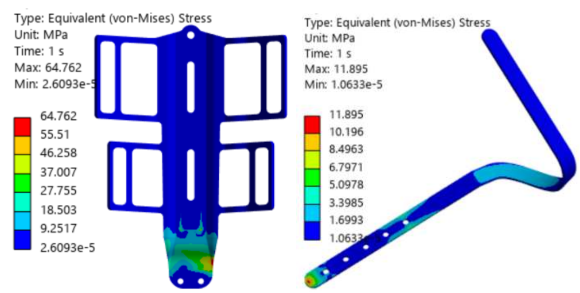


Fig. 8. Stress maps for components A1 and B2.

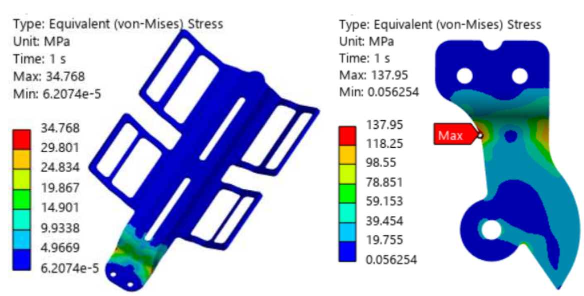


Fig. 9. Stress maps for components C3 and D4.

The plot depicting the overall distribution of displacement of 2.16 millimeters, maintaining it within the established limits is presented in Fig.11; this deformation was observed during the maximum loading conditions of 35 N.

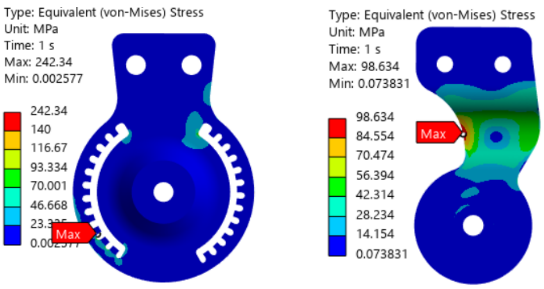


Fig. 10. Stress maps for components E5 and J10.

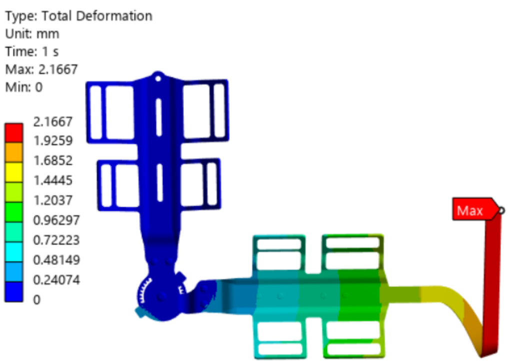


Fig. 11. Total deformation map [mm].

Table 4.
Eigenfrequency results.

Mode	Free-free [Hz]	Fixed constraint [Hz]
M1	50.2	9.2
M2	62.5	28.0
M3	91.2	40.5
M4	117.4	47.6
M5	122.3	77.0
M6	190.1	120.0
M7	225.1	147.4
M8	261.1	183.2
M9	322.1	260.9
M10	337.5	299.8
M11	363.4	337.1
M12	396.6	337.2

The results of the free-free modal analysis demonstrate that the first 1st mode of vibration is characterized by bilateral oscillation, with the maximum strain being observed in the frontal hand support region. The 2nd vibration mode is the front arm and forearm support. The 3rd vibration mode is the out of phase displacement between arm and forearm support, and the strain occurs at the forearm upper position. The 4th vibration mode is defined as the out-of-phase bending of the forearm and arm support components. The 5th vibration mode is symmetrical outreach on both sides of the sagittal plane. The 6th vibration mode is in the sagittal plane, and the oscillatory movement of the arm supports is directed along the horizontal axis. The first six structural mode shapes in free-free conditions are represented in Fig. 12.

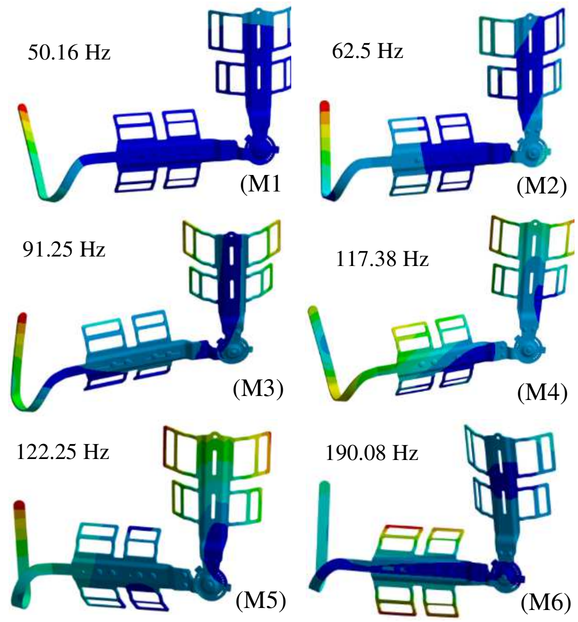


Fig. 12. Mode shapes M1 to M6 in free-free conditions.

The initial six structural mode shapes in fixed conditions are depicted in Fig. 13.

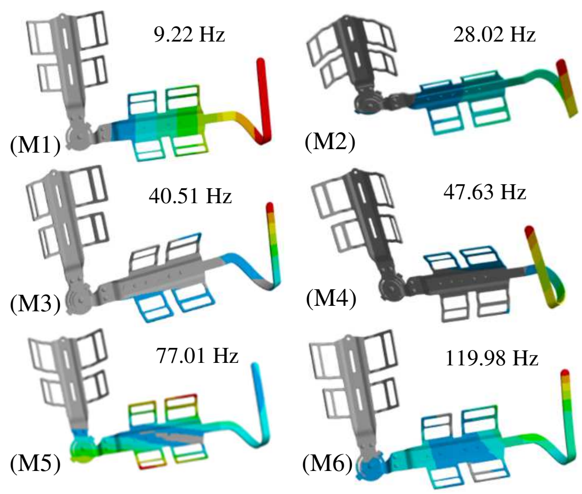


Fig. 13. Mode shapes M1 to M6 in fixed conditions.

The effective mass participation (EMS) results plot is represented in Fig. 14. The EMS factor is defined as the proportion of the system mass that engages in a particular mode. It provides an evaluation of the energy that is inherent within each resonant mode. In the context of complex system behavior, a mode that involves a substantial degree of participation is often considered a primary contributor to the system's dynamic response. 3 relevant mode shapes are identified at 9.2 Hz, 28 Hz, and 147.4 Hz.

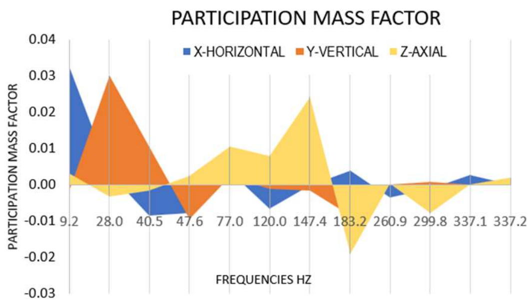


Fig. 14. Participation mass factor in fixed conditions.

7. DISCUSSION

The objective of the study was to examine and systematically document the angle of elbow positions in the context of maximum permissible motion during flexion-extension and pronation-supination movements, as part of a patient-centered rehabilitation program. Therefore, it was observed that the maximal rotational angle for elbow flexion prior to rehabilitation was recorded at 103.3°; post-rehabilitation, it was recorded at 128.1°. The torsiometer measurements indicated a 20.6° variation in total elbow pronation values post-rehabilitation program in comparison to pre-rehabilitation, exhibiting a 15.7° similarity in supination angle. The maximum angle of pronation that was recorded prior to the commencement of the rehabilitation program was 37.6°. Subsequent to the rehabilitation program, which was implemented two months later, a positive outcome was observed. The rehabilitation program resulted in a reduction of elbow stiffness, which, in turn, led to a notable increase in range of motion, reaching as high as 58.2 °.
In a correlative manner, supination angle measurements recorded prior to the initiation of the rehabilitation program indicated a value of 14.5°. The supination of the affected extremity was observed to reach up to 30.2° following the rehabilitation program. The treatment of choice for elbow stabilization is static immobilization, which is most often utilized for brief periods as a preventative measure following an injury or surgical intervention. The findings of the present study demonstrate that the finite element analysis technique is a reliably efficacious and economical method for analyzing elbow orthosis designs, exhibiting a high degree of accuracy and flexibility. The present investigation, which employed finite element analysis of the orthosis assembly, has yielded the conclusion that high stresses manifest in the central assembly elements of the orthosis mechanism. The maximum stresses observed in component E5 were recorded at approximately 242 MPa in the area of the locking pin. However, elevated levels of stress concentration persist in this teeth edge area, indicating the need for further examination and mitigation strategies to enhance its durability and reliability. To ensure a comprehensive assessment, further analysis is necessary to estimate the expected durability of the orthosis under conditions of demanding usage.

8. CONCLUSIONS

The present study is an in-depth examination, through a combination of virtual and experimental simulation, of the static and dynamic aspects of an orthosis system. This system is utilized to assist in the rehabilitation of patients who have been diagnosed with elbow joint dysfunction. A significant focal point in this regard pertains to the development and mechanical design of elbow orthoses, with a particular emphasis on their implications in elbow rehabilitation programs.

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STUDIUL TENSIUNILOR ȘI VIBRAȚIILOR UNUI MODEL VIRTUAL DE ORTEZĂ DE COT BAZAT PE ANALIZA CU ELEMENTE FINITE

Obiectivele principale ale acestei cercetări sunt atenuarea simptomelor asociate osteoartritei, cuprinzând disconfortul articular și mobilitate limitată, îmbunătățind astfel calitatea generală a vieții pacienților. În abordarea acestui subiect de cercetare, a fost folosită o abordare de modelare virtuală tridimensională (3D) pentru a genera o reprezentare a unei orteze fizice existente pe piață, care este frecvent utilizată în reabilitarea clinică a articulației cotului. Analiza cu elemente finite (FEA) a fost efectuată pentru a determina comportamentul elastic al unui model de orteză de cot și efectul acestuia asupra sistemului mână-braț în cazurile solicitante apărute în timpul utilizari acestei orteze de către pacient. O platformă de achiziție de date (Biometrics Ltd.) a fost utilizată pentru a documenta meticulos atât flexia-extensia cât și pronația-supinația cotului înainte și după un program de reabilitare implementat pentru un pacient afectat de boală osteoartrită.

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